UNIVERSITY OF ILLINOIS ENGINEERING EXPERIMENT STATION
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PERFORMANCE OF A GAS-FIRED FORCED-AIR HEATING SYSTEM IN RESEARCH RESIDENCE NO. 1

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PERFORMANCE OF A GAS-FIRED FORCED-AIR HEATING SYSTEM IN RESEARCH RESIDENCE NO. 1

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ABSTRACT

This bulletin is a report of an investigation conducted in the original Warm-Air Heating Research Residence under the terms of a cooperative agreement between the National Warm Air Heating and Air Conditioning Association and the Engineering Experiment Station of the University of Illinois. This investigation was conducted during the two heating seasons of 1941-42 and 1942-43, but the publication of the results has been deferred until this time. The data have been compiled and the bulletin has been prepared under the auspices of the American Gas Association.

In the operation of a gas-fired forced-air heating system a large number of combinations of air-flow rates, fuel-input rates, and the resultant air-temperature rises through the furnace can be used. These combinations include such variables as: single- and two-speed blower operation; single, two-stage, and modulated input burner operation; and low and high settings of the fan switch. Six combinations of these variables which are of practical interest were studied in an attempt to determine the optimum operating conditions from the standpoint of both comfort produced and cost of operation.

The room-air temperature differentials between the floor level and the breathing level were essentially the same for all the studies. At an indoor-outdoor temperature difference of 35 F, this differential was 2.5 F, while at an indoor-outdoor temperature difference of 55 F, this differential was between 3.5 and 4.0 F.

In general, the balance of air temperatures between rooms was best maintained for those arrangements in which the operation of the blower was practically continuous and the bonnet-air temperatures were maintained at relatively low values. This continuous operation of the blower was obtained by a combination of low fan-switch settings and low air-flow rates. Even though the air-flow rates maintained in these studies would be considered high by present-day standards, they were considerably lower than the flow rates commonly used at the time of the studies. The results indicated the desirability of using low air-flow rates and were a step in the development of the "continuous air circulation" principle advocated at the present time.

It was found that high air-flow rates and low fan-switch settings resulted in the lowest fuel consumptions. However, this was offset, to some extent, by the higher operating costs of the blower which accompanied the higher air-flow rates. The use of the two-stage burner resulted in no reduction in fuel consumption since it was not possible in this study to maintain a constant CO_2 content in the flue gas for the low-stage operation of the burner.

ABSTRACT (Concluded)

Taking into account the factors of temperature control, blower operation, and operating costs, it may be concluded that the results obtained with low air-flow rates and low fan-switch settings were the most satisfactory. Also, no particular advantage was gained by using a two-speed blower. Likewise, no significant advantage was gained by using the particular two-stage gas valve and two-stage thermostat utilized in this investigation.

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GLOSSARY

Air changes per hour — The number of changes of room-air volume per hour due to infiltration air leakage or introduction of ventilation air from outdoors. Based on standard air density of 0.075 lb per cu ft. See *Air recirculations.*

Air-flow rate — The rate of circulation of air in cu ft per min (cfm). Unless otherwise stated, all cfm values are for standard air density of 0.075 lb per cu ft. Also designated as flow rate.

Air recirculations per hour — The number of changes of room-air volume per hour due to recirculation of room air only. See *Air changes.*

Balance of room-air temperatures — Uniformity in room-air temperatures between different rooms served by a single room thermostat, when measured at the 30-in. level.

Blower — A centrifugal fan. The warm-air heating industry uses the term to distinguish centrifugal fans from propeller fans.

Blower cycle — One complete cycle of operation from the time the blower begins operation until it begins a second operation, following an off-period.

Bonnet capacity — The heat output of the furnace available at the bonnet, in Btu per hr for a specified air-temperature rise through the furnace.

Bonnet efficiency — The ratio of the bonnet capacity to the heat liberated in the furnace by the burner, also expressed as a percentage. For approved gas-fired forced-air furnaces, the rated bonnet efficiency is 80 percent.

Breathing-level temperature — Temperature of room air measured at a level 60 in. above the floor.

Burner cycle — One complete cycle of operation from the time the burner begins operation until it begins a second operation, following an off-period.

Ceiling-level temperature — Temperature of room air measured at a level 3 in. below the ceiling.

Continuous blower operation — A term used to designate a method of blower operation in which continuous operation is approached in average winter weather, but intermittent operation is obtained in mild weather.

Design heat loss — The calculated heat loss for a given space based on outdoor design conditions for the locality. In the text the outdoor design conditions are assumed as -10 F and 15 mph wind velocity.

Duct transmission efficiency — The ratio of the register delivery to bonnet capacity; also expressed as a percentage.

Floor-level temperature — Temperature of room air measured at a level 3 in. above the floor.

Fuel consumption — The consumption of fuel per 24 hr. In the case of gas-fired equipment the units are in terms of cu ft of gas per 24 hr.

Fuel-input rate — The rate of heat liberation in the furnace by the burner, expressed in Btu per hr.

Furnace bonnet — A central plenum, or collecting chamber, located usually above the furnace, in which the heated air is mixed before distribution to the duct system.

Furnace casing — The jacket or enclosure surrounding the furnace. In forced-air furnaces, the casing is usually insulated.

Flue-gas loss — The heat loss in the combustion gases, Btu per hr, as determined from the flue-gas temperature and the CO_2 content of flue gas. Unless otherwise stated, the flue-gas loss refers to the loss at the flue-gas outlet of the furnace. See *Heat transfer efficiency.*

Heat transfer efficiency — A measure of the effectiveness of the utilization of energy which is released in the furnace as represented by the heat imparted to the circulating air and to the environment of the furnace. The efficiency ratio is:

$$\frac{\text{(fuel input rate — flue-gas loss at furnace outlet)}}{\text{fuel input rate}}$$

This ratio has previously been referred to as "combustion efficiency."(1)* See also *Bonnet efficiency*.

Indoor-outdoor temperature difference — The difference in temperature between indoor air and outdoor air. Large temperature differences denote cold weather and small temperature differences indicate mild weather.

Intermittent blower operation — A term used to designate a method of blower operation in which on-periods and off-periods occur at regular frequencies during normal operation of the system.

Living zone — The space in a room between the floor level and the breathing level.

Modulated input burner — A burner provided with means to vary the rate of fuel input in a number of small increments between two fixed rates. This term also applies to a multi-stage burner.

Register delivery — The heat available at the registers, in Btu per hr. This is based on the air-flow rate through the register and the difference between register-air temperature and the air temperature at the return-air intake.

Single-speed blower — A blower which operates at a single fixed speed.

Single-stage burner — A burner provided with a gas valve having a single fixed rate of fuel input.

Temperature differential, room-air — The difference in air temperature in a room at two elevations. The breathing level, 60 in. from the floor, is considered as the reference level. See *Temperature gradient*.

Temperature gradient, room-air — A curve representing air temperatures existing at several elevations in a room at one station. See *Temperature differential*.

Thermostat differential setting — An adjustable setting in the room thermostat which governs the fluctuations in room-air temperature at the thermostat.

Two-speed blower — A blower which operates at either of two fixed speeds, high or low.

Two-stage burner — A burner provided with a gas valve having two different fixed rates of fuel input.

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* Parenthesized superscript numbers refer to correspondingly numbered entries in the References.

I. INTRODUCTION

1. Preliminary Statement

This bulletin is a report of an investigation conducted in the original Warm-Air Heating Research Residence under the terms of a cooperative agreement between the National Warm Air Heating and Air Conditioning Association and the Engineering Experiment Station of the University of Illinois. In this cooperative arrangement the Association was represented by a Research Advisory Committee, which consisted of the following members during the period of investigation (1941-43) reported in this bulletin:

F. G. Sedgwick (deceased), Chairman, Waterman-Waterbury Co., Minneapolis, Minn.

K. T. Davis, Bryant Heater Division of Affiliated Gas Equipment, Inc., Cleveland, Ohio.

G. W. Denges, Williamson Heater Company, Cincinnati, Ohio.

R. A. Gulick, May-Fiebeger Company, Newark, Ohio.

A. P. Livar, formerly with Chrysler Airtemp Division, Dayton, Ohio.

C. D. Lyford, Minneapolis-Honeywell Regulator Company, Minneapolis, Minn.

F. L. Meyer, The Meyer Furnace Company, Peoria, Illinois.

J. W. Norris, Lennox Furnace Company, Marshalltown, Iowa.

2. Acknowledgments

The investigation was conducted under the general administrative direction of Dean Emeritus M. L. Enger, former director of the Engineering Experiment Station; of Professor Emeritus O. A. Leutwiler, former head of the department of mechanical engineering; and of Professor N. A. Parker, head of the department of mechanical engineering. The work was under the direct supervision of Professor A. P. Kratz, research professor emeritus of the department of mechanical engineering. Acknowledgment is made for funds and technical assistance provided in 1949 and 1950 by the American Gas Association through its Committee on Domestic Gas Research for the compilation of data and preparation of the bulletin as a PAR Plan activity of the Association (A.G.A. Project DGR-7-CH).

3. Objectives of Investigation

The over-all objective of the investigations conducted in Research Residence No. 1 was to make studies of the performance characteristics of warm-air heating systems, with emphasis placed upon evaluation of the comfort produced by these systems and of the cost of producing that comfort.

In the operation of a gas-fired forced-air heating system a large number of combinations of air-flow rates, fuel-input rates, and the resultant air-temperature rises through the furnace can be used. These combinations include such variables as single- and two-speed blower operation, single, two-stage, and modulated input burner operation, and low and high settings of the fan switch. Specifically, the objective of this investigation was to determine and compare the performances of a conventional gas-fired forced warm-air heating system operating under the following conditions:

(a) With single-stage burner operation and a single-speed blower operating at 1225 cfm with low fan-switch settings. (The 1225 cfm is also referred to as a high air-flow rate.)

(b) With single-stage burner operation and a single-speed blower operating at 1225 cfm with high fan-switch settings.

(c) With single-stage burner operation and a two-speed blower operating at 800 or 1225 cfm with low fan-switch settings. (The 800 cfm is also referred to as a low air-flow rate.)

(d) With single-stage burner operation and a single-speed blower operating at 800 cfm with low fan-switch settings.

(e) With two-stage burner operation and a single-speed blower operating at 1225 cfm with low fan-switch settings.

(f) With two-stage burner operation and a two-speed blower operating at 800 or 1225 cfm with low fan-switch settings.

II. DESCRIPTION OF EQUIPMENT AND PROCEDURE

4. Research Residence

The investigation was conducted in Research Residence No. 1 in Urbana, Illinois, which was built, furnished, and completely equipped specifically for research in warm-air heating by the National Warm Air Heating and Air Conditioning Association in 1924. The Residence, which was sold in 1946 and replaced by the smaller Research Residence No. 2, has been described in detail in Engineering Experiment Station Bulletins 189[2] and 266.[3] The floor plans are shown in Fig. 1. The Residence was a two-and-one-half-story structure of frame construction with side walls and ceiling insulated with mineral wool. All of the fifty windows with the exception of two small quarter-round windows on the third story were provided with tightly fitting storm sash.

The total volume of the heated space was approximately 17,540 cu ft. The design heat losses were approximately 51,140 Btu per hr, at an indoor-outdoor temperature difference of 80 F. The Research Residence was occupied by four people in 1941-42 and by three people in 1942-43.

5. Heating System

The gas-fired forced-air furnace was equipped with steel heat exchangers, and with a blower which was installed in a blower cabinet connected directly to the furnace, as shown in Fig. 2. The furnace had a rated bonnet capacity of 72,000 Btu per hr at an input of 90,000 Btu per hr. The rated register delivery based upon a duct transmission efficiency of 85 percent was 61,200 Btu per hr, or only 20 percent greater than the design heat loss of the Residence. Natural gas with a calorific value of 1000 Btu per cu ft was used as the fuel.

A plan of the duct system connected to the furnace is shown in Fig. 3. The single-trunk duct, transmitting the warm air from the furnace, included a venturi air-measuring section. The air-flow rate through the duct system was determined at this section by means of a pitot tube which was calibrated in place in the center of the 9-in.-by-8-in. throat of the venturi section. For an air-flow rate of approximately 1200 cfm the resistance of the venturi section alone introduced a pressure loss of about 0.085 in. of water above that of the remainder of the

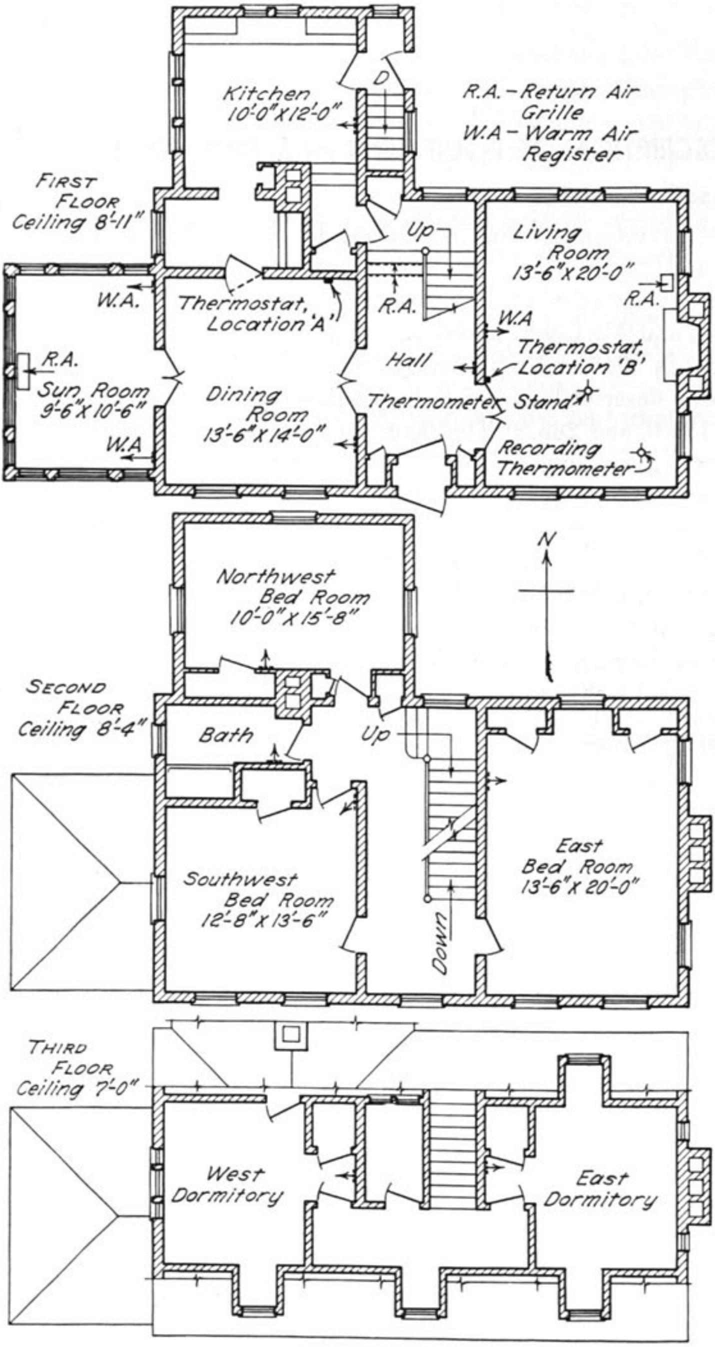

Fig. 1. Floor Plans of Research Residence No. 1

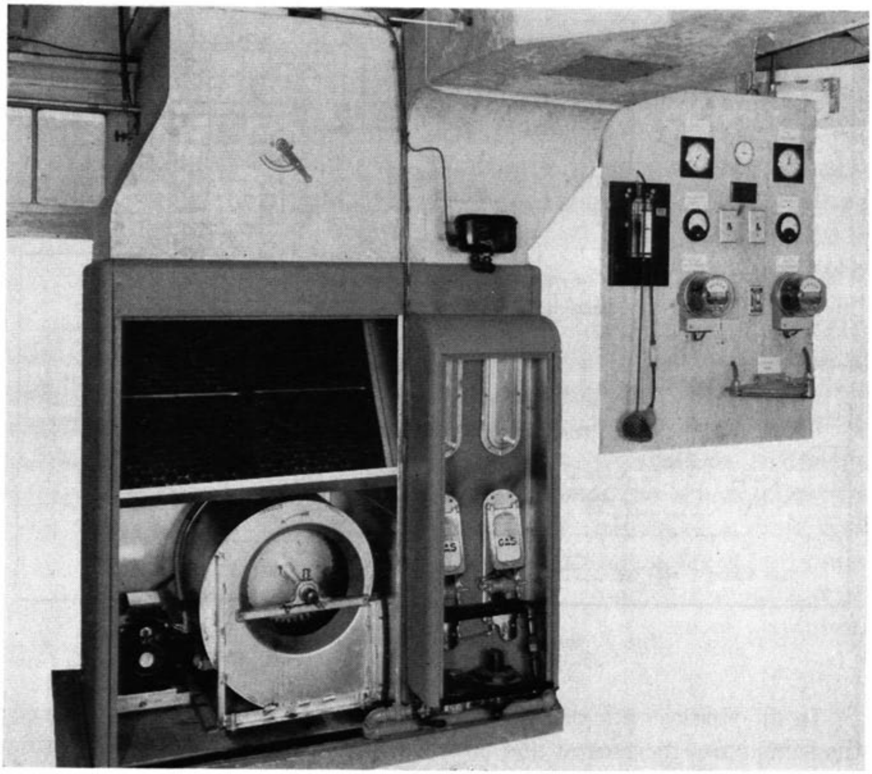

Fig. 2. Gas-Fired Forced-Air Furnace with Front Covers Removed

duct system. The warm-air registers were located on the inside walls approximately 7 ft above the floor.

6. Automatic Controls

The room thermostat was of the heat-anticipating type and was located on an inside wall of the dining room 60 in. from the floor. In the studies with the single-speed blower and the single-stage burner, the operation of the burner was controlled by means of the room thermostat, while a fan switch was used to start the blower at a predetermined bonnet-air temperature and to stop the blower when the bonnet-air temperature decreased to a lower value. In this, as well as in all succeeding studies, a limit control was included in the burner circuit to prevent operation of the burner if the bonnet-air temperature exceeded a predetermined limit for safe operation.

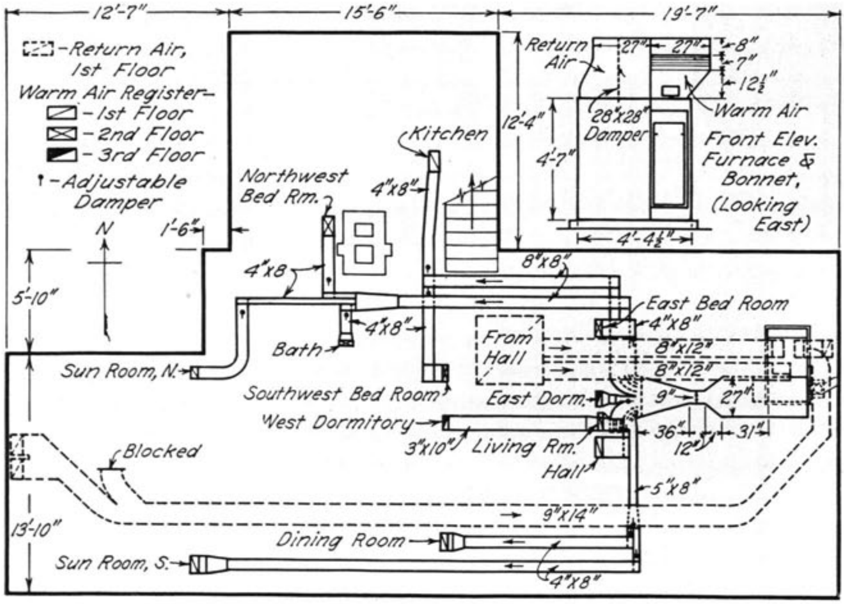

Fig. 3. Basement Plan and Layout of Duct System

In the studies with the two-speed blower and the single-stage burner, the same room thermostat and blower motor were used but modifications were made in the electrical connections to the motor and fan switch. The blower started to operate on low speed when the bonnet-air temperature increased to a value corresponding to the cut-in point of the fan switch and continued operating on the low speed until the temperature increased to the high-speed cut-in point of the fan switch. When the temperature decreased to the high-speed cut-out point of the fan switch, the blower then returned to low-speed operation and continued to operate at this speed until the temperature was reduced to the cut-out point.

In the studies conducted with the two-speed blower and the two-stage burner the blower controls were not changed, but the single-stage room thermostat and gas valve were replaced with a two-stage room thermostat and a two-stage gas valve. The wiring diagram for the two-stage gas valve and room thermostat is shown in Fig. 4. When the room-air temperature decreased to a value corresponding to the cut-in point of the room thermostat, the circuit for the low-stage gas valve was completed and low-stage burner operation of the burner was obtained. If the room-air temperature decreased an additional predetermined amount, the circuit for the high-stage gas valve was completed, and high-stage burner operation resulted. The room thermostat contained a heat-anticipating element in the high-stage circuit only.

7. Procedure for Normal Operation

For each of the six main series the average of the air temperatures in all of the rooms was maintained at approximately 72 F at the breathing level both day and night. All windows remained closed. Observations of weather, room-air temperatures, indoor relative humidities, and other incidental data were made daily at 7:00 a.m., 11:00 a.m., 4:00 p.m., and 10:00 p.m., and average daily values were determined. Complete data were obtained for each 24-hr period of the fuel consumption, the total times of operation of both the blower and the burner, the total electrical inputs to the blower motor and to the burner and the total number of on-periods for both the blower and the burner. In addition, continuous 24-hr records of temperatures, draft at the base of the chimney, and the CO_2 content in the flue gas were obtained. By means of a draft hood supplied as a standard part of the furnace and installed at the flue outlet, basement air was admitted into the chimney to maintain a stack draft which was substantially zero at all times. For each series, data were obtained over a wide range of weather conditions.

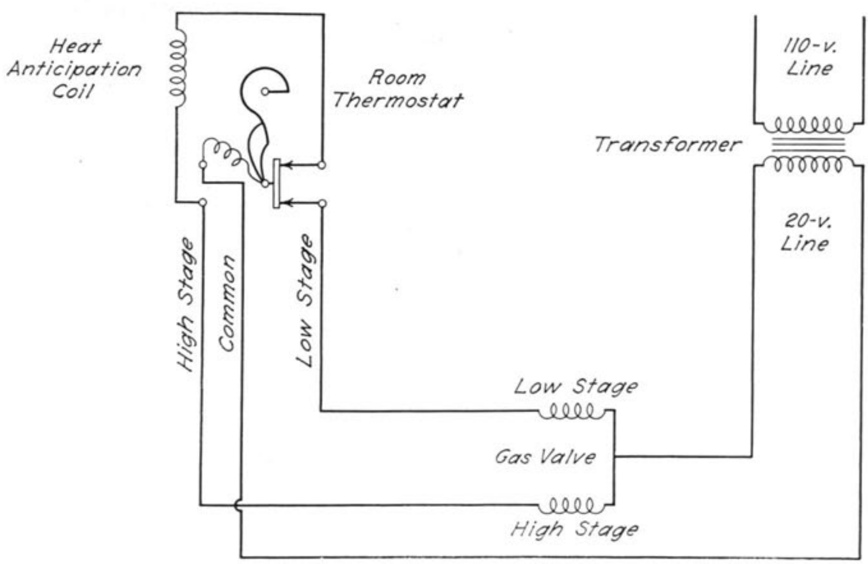

Fig. 4. Wiring Diagram for Two-Stage Gas Valve and Room Thermostat

From preliminary observations of the data, a time lag of approximately two hours was noted between the time of change in outdoor temperature and a resultant change in the heating plant operational demand. By plotting the data of the plant performance for a 24-hr period beginning at 11 a.m. against the average value of indoor-outdoor temperature difference obtained for a 24-hr period beginning at 9 a.m., it was observed that the deviations of the individual points from the average curve were minimized. Hence, for the purpose of this bulletin, a time offset of two hours was used in determining the average indoor-outdoor temperature difference.

III. TESTS FOR CAPACITY AND EFFICIENCY OF FURNACE

8. General Statement

In order to determine the bonnet capacity and efficiency of the furnace for various combinations of blower speeds and fuel-input rates, tests were made under steady-state conditions with both the burner and the blower operating continuously. The air-flow rate, the fuel-input rate, the draft in the combustion chamber, and the amount of air required for combustion were maintained constant during the two-hour test period. The temperature of the inlet air was maintained at about 70 F. These tests which corresponded to the usual laboratory tests for the determination of the bonnet capacity provided data for the furnace performance only, without reference to the structure in which it was placed.

The items referred to as capacity, heat liberation, bonnet efficiency, and heat transfer efficiency were defined by the following equations:

$$\text{Bonnet capacity, Btu per hr} = 0.24W\,(t_b - t_i)$$

$$\text{Heat liberated in furnace, Btu per hr} = CH.$$

$$\text{Bonnet efficiency, percent} = \frac{0.24W\,(t_b - t_i)}{CH} \times 100$$

$$\text{Heat transfer efficiency, percent} = \frac{CH\,(100 - L_g)}{CH} = 100 - L_g$$

in which

W = weight rate of air flow, lb per hr
0.24 = mean specific heat of air, Btu per lb per F
C = combustion rate of gas, cu ft per hr
H = calorific value of gas, Btu per cu ft
t_i = temperature of air at inlet to furnace, F
t_b = temperature of air at furnace bonnet, F
L_g = losses in flue gas, in percent of heat liberated

The four possible combinations of blower speeds and fuel-input rates maintained in these steady-state performance tests, as listed in Table 1, correspond to those maintained in later studies under normal operation.

9. Discussion of Results

The furnace was designed for an input rate of 90,000 Btu per hr. In these studies the flue-gas openings, primary-air shutter adjustment, and

Table 1

Results of Tests for Furnace Capacity and Efficiency

The operating conditions for Test No. 1 correspond to series A and B (see Table 2); for Test No. 2 and 3 to series C and D (see Table 4); for Test No. 4 to series E (see Table 6); and for Test No. 5 to series F (see Table 6).

Test No.	Fuel-Input Rate, Btu per hr	Blower Speed, rpm	Air-Flow Rate, cfm	Temp. Rise through Furnace, F	CO_2, percent	Flue-Gas Temp., F	Flue-Gas Loss, percent*	Heat Transfer Efficiency, percent	Bonnet Efficiency, percent	Bonnet Capacity, Btu per hr
1	89 700 (High-stage)	538 (High speed)	1225	50.4	8.1	411	20.0	80.0	74.2	66 650
2	89 700 (High-stage)	360 (Low speed)	802	74.1	8.1	462	21.8	78.2	69.9	62 150
3†	89 700 (High-stage)	360 (Low speed)	800	72.5	8.4	463	20.8	79.2	67.5	60 500
4	60 000 (Low-stage)	538 (High speed)	1225	35.7	5.6	315	20.8	79.2	75.6	45 620
5	59 600 (Low-stage)	358 (Low speed)	769	49.4	5.7	381	22.0	78.0	70.0	41 680

* Obtained from Univ. of Ill. Eng. Exp. Sta. Circ. 44, "Combustion Efficiencies as Related to Performance of Domestic Heating Plants."
† Test No. 3 was conducted under same operating conditions as Test No. 2 and provided means of determining consistency of results.

secondary-air aeration produced approximately 8 percent CO_2 content of the flue gases at rated input. However, when the burner was operating at low stage with an input rate of 60,000 Btu per hr, the same adjustments caused a reduction in the CO_2 content of the flue gases to 5.6 percent. The internal draft within the heat exchanger was reduced only slightly by the reduction in fuel-input rate; but since the secondary-air openings were unchanged, the excess air increased and caused a corresponding reduction in the CO_2 content of the flue gases. Since adjustments of the primary and secondary air for low- and high-stage operations of the burner would require complicated controls, the CO_2 content of the flue gas was maintained at 5.6 percent on the low-stage operation to insure complete combustion with high-stage operation.

The results of the capacity and efficiency tests shown in Table 1 indicate that for the same fuel-input rate, increasing the air-flow rate over the heating surface caused a minor increase in heat transfer efficiency and a slightly greater increase in bonnet efficiency, the difference between these two efficiencies presumably being due to the lowering of the casing losses. Such conclusions are supported by a comparison at high-stage input rates of test 1 with test 2, and at low-stage input rates of test 4 with test 5. In other words, an appreciable difference in bonnet efficiency was not reflected in a corresponding difference in combustion efficiency.

For a constant air-flow rate through the furnace casing, a comparison of efficiency data recorded in test 1, indicates that the heat transfer efficiency decreased slightly as a result of reduced input but that the bonnet efficiency remained constant or was slightly increased. The heat transfer efficiency was not altered appreciably by decreasing the fuel-input rate, since any possible gain due to the lower flue-gas temperatures was offset by a reduction in the CO_2 content of the flue gas. This finding on heat transfer efficiency variation is in accord with previous research[4] conducted on gas-fired furnaces. On the basis of these tests under steady-state conditions, no definite conclusion was reached as to the most desirable fuel-input or air-flow rate under normal operation. For the purpose of establishing such relationships, the following series of comprehensive studies were made.

IV. RESULTS WITH A SINGLE-STAGE BURNER

10. General Statement

The comparison of warm-air heating systems has been based primarily on the evaluation of comfort produced by the system and the cost of producing the comfort. Comfort is an elusive item to evaluate, depending as it does upon a large number of factors, such as air temperatures, surface temperatures, relative humidity, and air movement, as well as a number of less tangible items, such as odor, noise, and dust content. The indoor relative humidity was comparable for all studies since no attempt was made to add moisture to the air by the humidifier. Since the room-air temperature is the major item of comfort affected by burner and blower operation, the discussion of comfort has been limited to this particular phase.

The study of the room-air temperatures was devoted primarily to conditions obtained in the living zone between the floor level and the breathing level, since the zone above the breathing level is of little significance in determining the comfort of occupants. However, from the standpoint of maintaining a minimum heat loss through the upper exposed walls and through the ceiling, a low air temperature at the ceiling is desirable. One method for evaluating the comfort conditions in the living zone has been to measure the room-air temperature differential between the floor level and breathing level, a small differential being more desirable than a large one. Another measure of evaluation has been to determine the variations in room-air temperatures with respect to time. The temperature variation during one complete cycle of the blower operation has been shown[5] to be dependent on the average length of the off-period of the blower and the number of blower operations per day. Since a shorter off-period results in a more continuous heat supply to the room and smaller temperature variations in the living zone, the average length of the blower off-period has been used as one index for evaluating the comparative comfort provided by different methods of control of forced warm-air systems.

The total cost of producing the comfort is the sum of the costs of the fuel, and electrical inputs to the blower motor and to the gas valve. Although the fuel cost is the major item, the cost of operating the blower motor must also be considered. The cost of operating the gas valve is usually negligible. Comparisons have been made in terms of fuel consumption and electrical inputs and not in terms of dollars since unit prices of fuel and electricity vary greatly.

The results obtained were influenced to some extent by the conditions which were imposed and by the equipment used. For example, the selection of 1225 cfm for high-speed operation of the two-speed blower was arbitrary, and the results obtained would have been modified if a different air-flow rate had been used. Also, the relative electrical costs for a two-speed blower motor and a single-speed blower motor were dependent on the characteristics of the motor. These limitations which apply to practically all studies made under service conditions do not invalidate the results obtained.

11. Comparison of Results of a Single-Speed Blower Operated at a High Flow Rate with Low and High Fan-Switch Settings (Series A and B)

The operating conditions for series A and B, shown in Table 2, provided a means for comparing the effect of high and low fan-switch settings upon the performance of gas-fired forced-air system. With a fuel-input rate of 90,000 Btu per hr and an air-flow rate of 1225 cfm with

Table 2
Operating Conditions for Series A and B

Series	Air-Flow Rate, cfm	Fan-Switch Settings, F	Blower Speed, rpm	Fuel-Input Rate, Btu per hr
A	High: 1225	Cut-in: 100 Cut-out: 80	Single-Speed High: 538	Single-stage, 90 000
B	High: 1225	Cut-in: 155 Cut-out: 130	Single-Speed High: 538	Single-stage, 90 000

the high-speed blower, an air temperature rise of 50 F from inlet to discharge of the furnace was obtained. As indicated in Table 1 this temperature rise corresponded to steady-state conditions obtained after a long period of continuous burner and blower operation, and not to the rises normally obtained during intermittent operation of the burner and blower. The temperature rise of 50 F is considerably smaller than the 70 to 100 F specified in the present "Approval Requirements,"[6] so that the air-flow rate of 1225 cfm was considerably greater than the 875 cfm and 612 cfm which would have been required for temperature rises of 70 F and 100 F, respectively. However, the flow rate of 1225 cfm was equivalent to only 4.2 air recirculations per hr as compared to the 6 air recirculations per hr commonly considered as necessary for satisfactory operation when these studies were conducted. If 6 air recirculations per hr had been used, the air-flow rate would have been 1754 cfm, and it would have been necessary to use a larger blower than that provided with the furnace. It is apparent that the use of an arbitrary number of air recirculations, such as 6 per hr, will not apply to a wide range of house sizes and heat losses. In the case of the Residence the volume of heated space was large, but the heat loss was small because of the extensive use of insulation and storm sash. In some of the other studies reported in this bulletin even further deviations from the 6 air recirculations per hr were made. Since it was not possible to circulate more than 1225 cfm without changing the blower pulley and motor, this flow rate was considered as the maximum practical delivery for this investigation even though common practice at the time would have required 1754 cfm. For these studies the air-flow rate of 1225 cfm was designated as "high-flow rate."

With a fuel-input rate of 90,000 Btu per hr and a relatively large air-flow rate of 1225 cfm, the performance of the heating system was markedly affected by the setting of the controls, particularly the fan switch. For series A, the cut-in temperature of the fan switch was 100 F and the cut-out temperature was 80 F whereas for series B the corresponding settings were approximately 50 F higher. It should be noted that at the time of these studies the control settings for series B were commonly used in practice. Since a low setting of the fan switch would result in longer blower operations and a resulting decrease in the length of off-periods, series A was considered as a possible solution for improving the performance obtained with series B.

(a) *Room-Air Temperature Differentials and Variations*

The room-air temperature differentials between the three elevations in the rooms is shown in Table 3. These differentials, which were an average value for all of the rooms in the Residence increased as the indoor-outdoor temperature difference increased. In all cases the temperature differentials from floor level to breathing level were practically the same for series A and series B.

The temperatures maintained at the breathing level of the various rooms in the Residence were also of interest. For series A the dampers in the branch ducts that delivered warm air to the rooms were initially adjusted to give approximately the same breathing level temperatures in all of the rooms. The room thermostat was located in the dining room of the first story and no damper adjustments were made in changing from one test series to the other. With series B, the temperatures at the breathing level of the second- and third-story rooms were approximately 2 F higher than those of the first-story rooms. This difference in the

Table 3
Room-Air Temperature Differentials for Series A and B

Indoor-Outdoor Temperature Difference, F		20	35	55	65
	Series	Temperature Differentials, F			
Floor Level to Breathing Level	A	1.3	2.5	3.9	4.6
	B	1.8	2.6	4.0	4.6
Breathing Level to Ceiling Level	A	1.0	1.5	2.1	2.3
	B	1.6	2.3	3.0	3.2
Floor Level to Ceiling Level	A	2.3	4.0	6.0	6.9
	B	3.4	4.9	7.0	7.8

temperatures between the first-story rooms and rooms on the second and third stories resulted from "gravity" action during the off-period of the blower. The factors which caused this unbalance may be seen in Fig. 5, which shows bonnet-air temperatures during one cycle of burner operation for both series A and B. For series A the blower operated about 5½ min, at the end of which time the bonnet-air temperature had been reduced to 87.5 F. During the off-period the temperature gradually rose to 97 F. On the other hand, for series B the blower operated only about 1 min, at the end of which time the bonnet-air temperature was reduced to 130 F. During the long off-period the temperature increased sharply

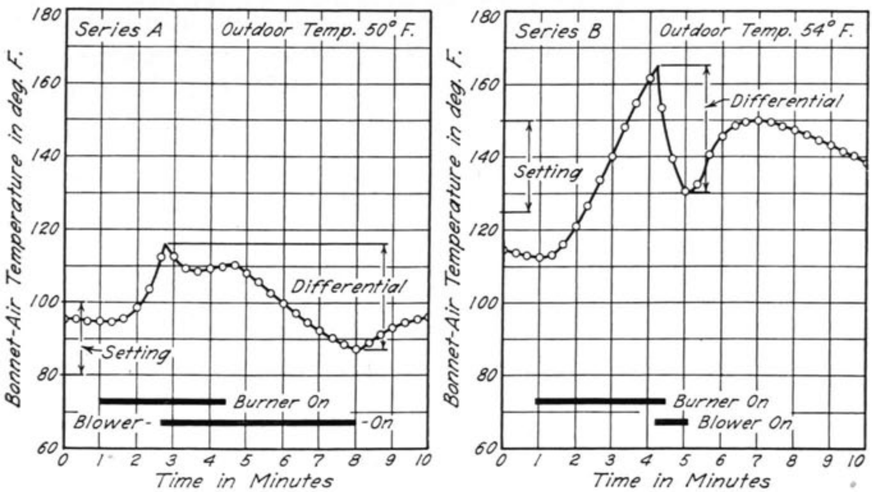

Fig. 5. Effect of Fan-Switch Settings on Bonnet-Air Temperature

to 150 F with an average value greater than 140 F. A noticeable gravity action occurred with this higher bonnet-air temperature. For a given weather condition, this unbalance resulting from gravity action could have been compensated for by changes in the damper settings. However, any adjustment of the dampers which would be suitable for this given case would not be suitable for other weather conditions. Hence, from the standpoint of the temperature between rooms, series A provided better results than did series B.

(b) *Performance of the Blower*

For both series the averages of the maximum and minimum bonnet air temperatures were essentially constant over the range of indoor-outdoor temperature differences shown in Fig. 6. Series A produced the lower bonnet-air temperatures as a result of the lower settings of the fan switch.

The total time of operation of the blower for series A was approximately twice that experienced with series B, and the electrical inputs to the blower motor were correspondingly greater. The electrical inputs shown in Fig. 6 were larger than for a normal installation since the pressure loss of the venturi air-measuring section in the main-trunk duct was nearly equal to the loss in the remainder of the duct system. This large loss necessitated a higher blower speed than would have been required in a normal system without the venturi section.

As shown in Fig. 6, at an indoor-outdoor temperature difference of 55 F the average length of off-period was 0.05 hr or 3 min for series A as compared with 0.15 hr or 9 min for series B. As indicated in Section 10, a shorter off-period results in a more continuous heat supply to the room and a smaller temperature variation in the living zone and is, therefore, more desirable than a long off-period.

(c) *Performance of the Burner*

As shown in Fig. 7, the average maximum flue-gas temperatures obtained with series A were approximately 100 F lower than those for series B. Since both series were operated with the same fuel-input rate and blower speed, the difference in maximum flue-gas temperatures may be attributed to the shorter length of the operating period of the blower with series B. The burner operated for a longer period before the blower started because of the higher cut-in temperature of the fan switch, and as a result the flue-gas temperature rose to a higher value than that experienced with series A. Similarly, the blower operated a shorter period after the burner was shut off for series B because of the higher cut-out temperature, and the flue-gas temperatures remained higher during the off-period of the blower.

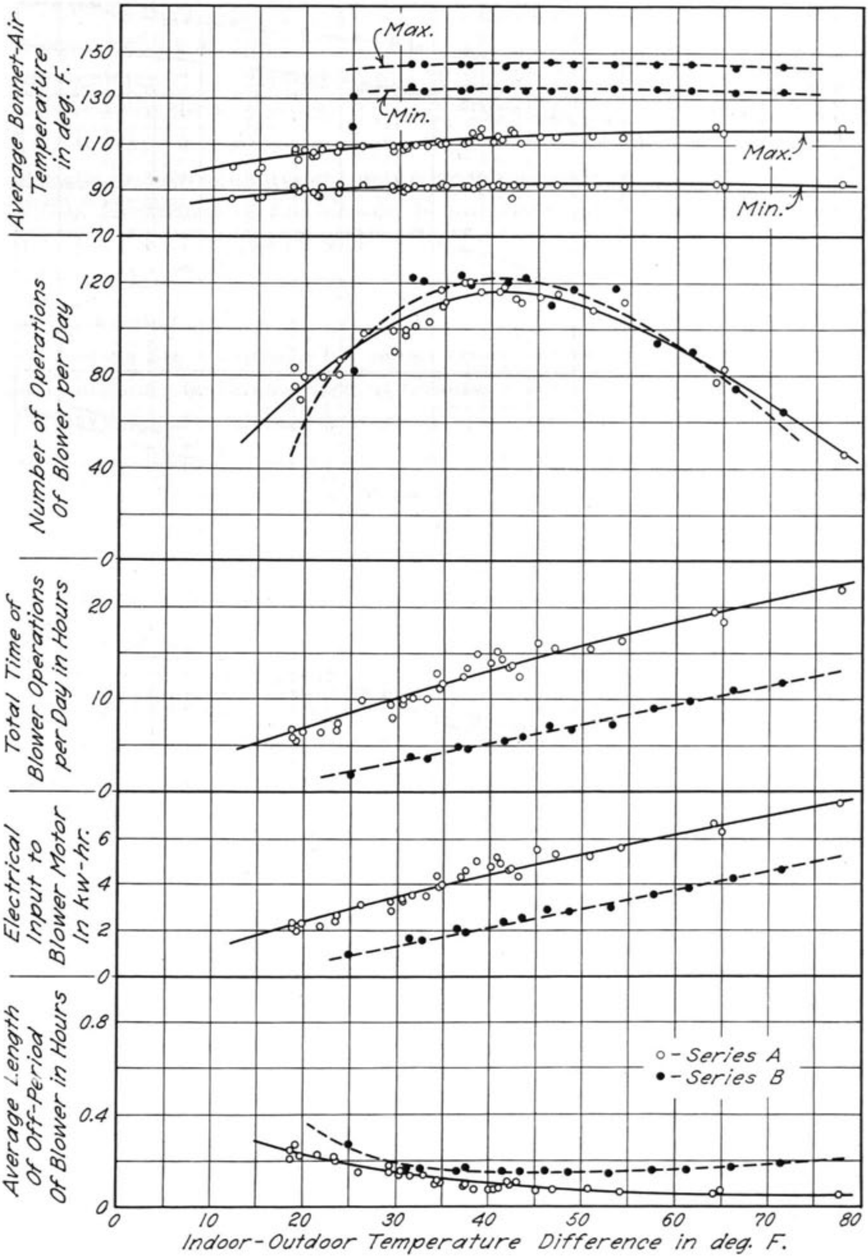

Fig. 6. Blower Performance Curves for Series A and B

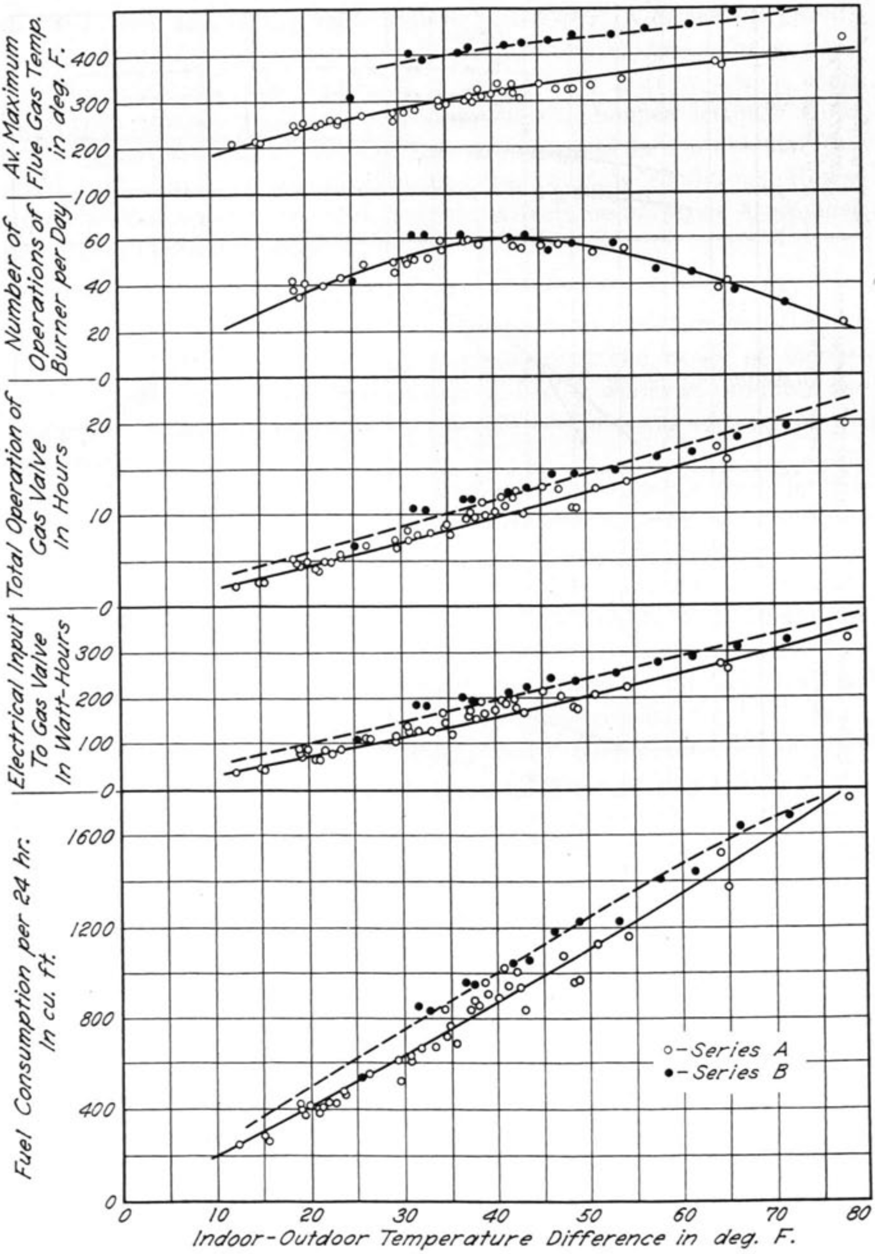

Fig. 7. Burner Performance Curves for Series A and B

Curves representing the fuel consumption for series A and B are shown at the bottom of Fig. 7. The consumption for series B was 16 percent greater than that for series A at an indoor-outdoor temperature difference of 35 F and was 11 percent greater at a difference of 55 F. The increase in fuel consumption may be accounted for by the greater flue-gas loss accompanying the higher flue-gas temperatures, particularly during off-periods of the blower. From the standpoint of fuel consumption, therefore, more favorable results were obtained with series A than with series B.

(d) *Summary*

The results obtained with lower settings of the fan switch and a high flow rate may be summarized as follows:

(1) Longer operating periods of the blower accompanied the lower bonnet-air temperatures which reduced the room-air temperature variations in the living zone.

(2) Lower bonnet-air temperatures and shorter off-periods reduced the "gravity" action during the off-period of the blower, and therefore resulted in a better temperature balance between the first, second, and third stories.

12. Comparison of Results with a Two-Speed Blower to Those with a Single-Speed Blower Operated at a Low Flow Rate (Series C and D)

The previous studies[5] made with a two-speed blower are of interest. In these earlier studies the air-flow rates were 1000 cfm for low-speed operation and 1675 cfm for high-speed operation. The performance obtained with the two-speed blower operation was compared with that obtained with high-speed operation only. The results thus obtained indicated that the two-speed operation was better than only the high-speed operation.

A similar study of two-speed blower operation using lower flow rates which would reduce the electrical input, maintain long operating periods of the blower, and reduce the velocity of the air discharged from the register was considered desirable.

Hence, for the studies reported in this bulletin the air-flow rates for series C were 800 cfm for low-speed operation and 1225 cfm for high-speed operation. Furthermore, the performance obtained with series C was compared with that for series D, in which only low-speed operation was used. The operating conditions for these two series are given in Table 4.

In series D, the controls were adjusted so that the blower operated at low speed only, and the settings of the fan switch were adjusted to extremely low values. The air-flow rate at this low speed was 800 cfm,

Table 4
Operating Conditions for Series C and D

Series	Air-Flow Rate, cfm	Fan-Switch Settings, F	Blower Speed, rpm	Fuel-Input Rate, Btu per hr
C	Low: 800 High: 1225	Cut-in: 90 Low to High: 120 High to Low: 95 Cut-out: 80	Two-speed Low: 360 High: 538	Single-stage 90 000
D	Low: 800	Cut-in: 90 Cut-out: 80	Single-speed Low: 360	Single-stage 90 000

equivalent to 2.7 recirculations of air per hr, and was designated as a low flow rate. As shown in Table 1 continuous operation of the burner and blower under these conditions was accompanied by a temperature rise through the furnace of approximately 73 F. The purpose of these two series was to compare the performance obtained with a two-speed blower and a single-speed blower operated at a low flow rate. The fan-switch settings for low flow-rate operation were the same for each series; therefore, until the indoor-outdoor temperature difference was sufficiently large to cause high-speed operation of the blower for series C, the performance characteristics for the two series were identical.

(a) *Room-Air Temperature Differentials and Variations*

The room-air temperature differentials in the living zone for series C and D, shown in Table 5, were essentially the same for these two series. A slight reduction in the temperature at the ceiling level was obtained with series C, particularly for indoor-outdoor temperature differences greater than 55 F.

In these studies, for which the low flow rate was 800 cfm and the high flow rate was 1225 cfm, no unbalance in room-air temperatures

Table 5
Room-Air Temperature Differentials for Series C and D

Indoor-Outdoor Temperature Difference, F		20	35	55	65
	Series	Temperature Differentials, F			
Floor Level to Breathing Level	C	1.5	2.5	3.7	4.4
	D	1.5	2.4	3.7	4.4
Breathing Level to Ceiling Level	C	1.2	1.7	2.3	2.5
	D	1.2	2.0	3.0	3.4
Floor Level to Ceiling Level	C	2.7	4.2	6.0	6.9
	D	2.7	4.4	6.7	7.8

between rooms was noted over the entire range of weather conditions. In this case the low speed was 67 percent of the high speed. Furthermore, the maximum bonnet-air temperature accompanying the low-speed operation was only about 140 F and the register-air temperatures were even less than 140 F. In later tests, conducted in the laboratory, an unbalancing action was observed when the low-speed operation was reduced to less than about 50 percent of the high-speed and when the register-air temperatures were at high values.

(b) *Performance of the Blower*

Figure 8 shows that practically identical blower performance was obtained for both series C and D between 10 F and 40 F indoor-outdoor temperature differences. At a temperature difference of 40 F, the length of burner operation was such that the maximum bonnet-air temperature was 120 F. In the case of series C, this value of 120 F corresponded to the high-speed cut-in temperature for the blower so that for indoor-outdoor temperature differences greater than 40 F the blower operated at high speed. This high-speed blower operation resulted in a maximum temperature rise of 50 F through the furnace, as shown by Test No. 1 in Table 1, so that the average maximum bonnet-air temperature, as shown at the top of Fig. 8, did not rise above 120 F. However, in the case of series D since the blower operated at a low flow rate over the entire range of weather conditions, the maximum bonnet-air temperature continued to rise above 120 F as the weather became colder.

The frequency of operation of the blower was the same in each series for comparable weather. At indoor-outdoor temperature differences exceeding 40 F the total time of operation for the blower was approximately three hours less for series C than for series D. This resulted from the fact that with high-speed operation in series C the blower operated for a shorter period after the burner was shut off. Although a smaller total time of blower operation resulted with series C than for series D, the electrical input to the blower was higher because of the greater input required to operate the blower at high speed. For both series C and D the average length of off-periods was negligibly small. The results obtained with only low-speed operation, series D, compared favorably in all respects with those obtained with two-speed operation, series C, over the entire range of weather conditions.

(c) *Performance of the Burner*

As may be seen from the performance curves for the burner at the top of Fig. 9, the average maximum flue-gas temperatures increased as the weather became colder. The values obtained with series C were

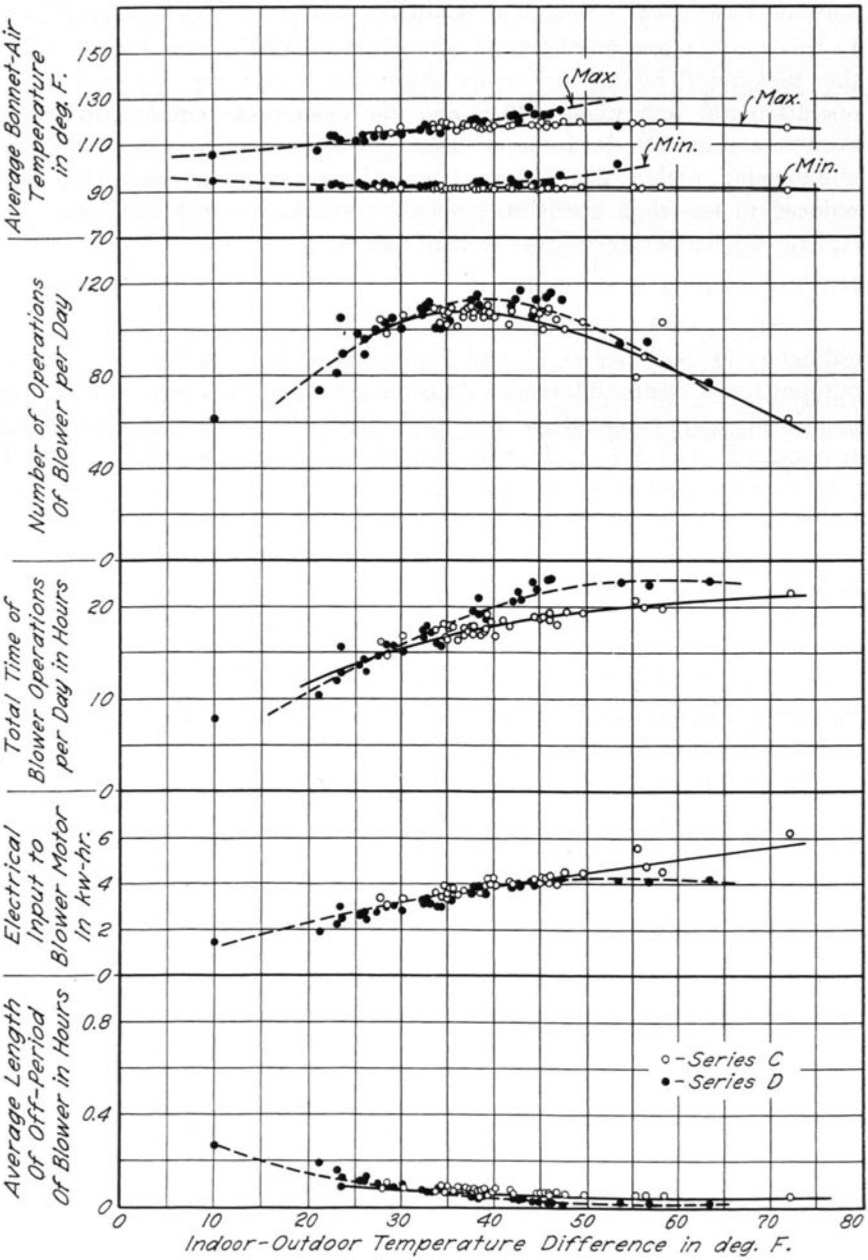

Fig. 8. Blower Performance Curves for Series C and D

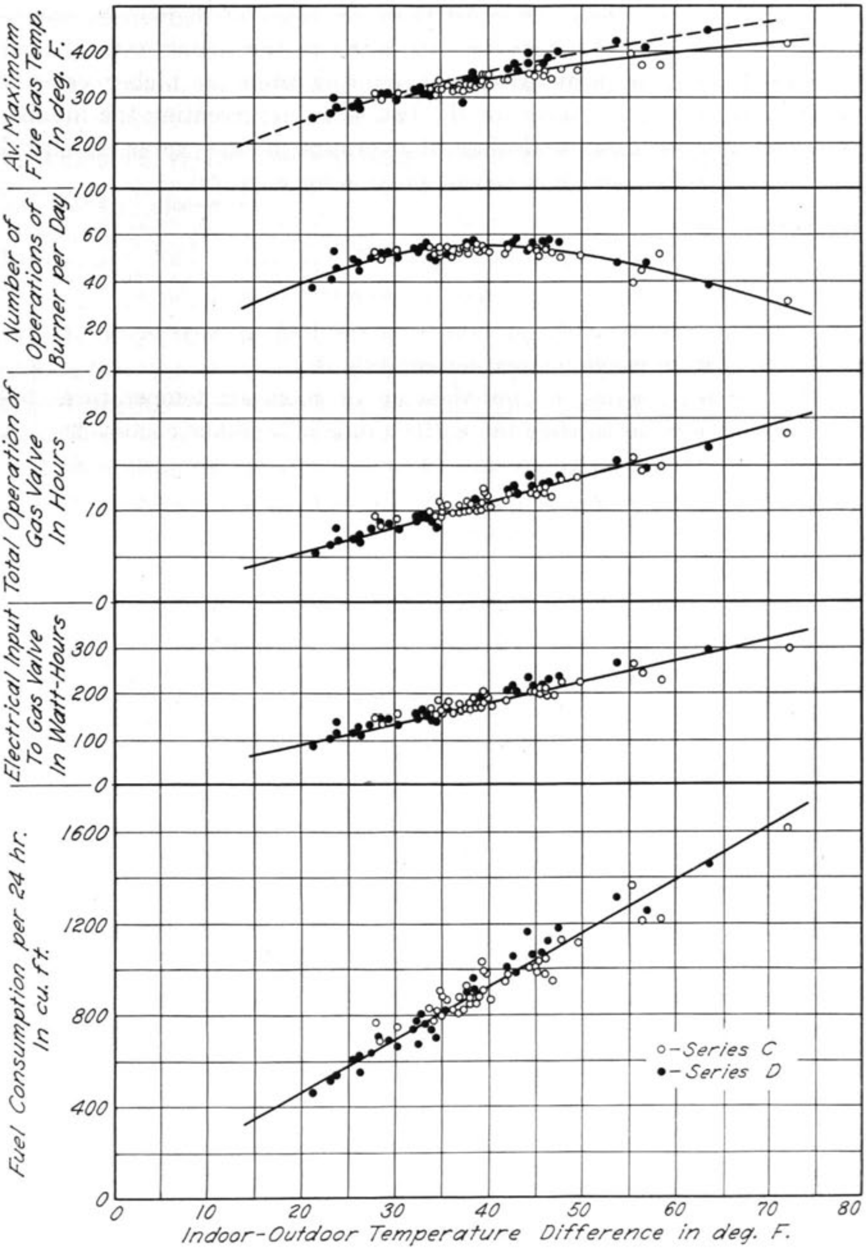

Fig. 9. Burner Performance Curves for Series C and D

slightly lower than those for series D in the range of high-speed operation of the blower. This may be attributed to the higher rate of heat transfer through the heat exchanger resulting from the higher velocity of circulated air. The curves for the two series representing the number of operations per day, total time of operation of gas valve, electrical input to gas valve, and fuel consumption were identical.

(d) *Summary*

The results obtained with two-speed operation and single-speed operation with a low flow rate may be summarized as follows:

(1) The two-speed blower operation resulted in satisfactory conditions over a wide range of weather conditions.

(2) For both series, no unbalancing of room-air temperatures between rooms was noted over the entire range of weather conditions.

(3) The single-speed blower operation at a low flow rate also produced satisfactory conditions at slightly lower electrical input than was obtained with the two-speed blower operation.

V. RESULTS WITH TWO-STAGE BURNER (SERIES E AND F)

13. General Statement

The heat loss from any house is continuous during the heating season but varies in magnitude depending upon the weather. The ideal method of operation of the heating system would be that in which the register delivery would be continuous but varied in rate to exactly balance the rate of heat loss. For the purpose of approaching this ideal condition, a number of possible methods of burner and blower operation can be used. Some of these methods involve relatively simple adjustments of the controls for the burner and blower while the others entail modifications of the gas valve as well as the controls. For example, the following three methods can be used:

(1) Intermittent operation of the burner with a fixed fuel-input rate.

(2) Modulation of the fuel-input rate between fixed maximum and minimum values (multi-stage operation).

(3) Intermittent operation of the burner with either of two input rates, (fixed maximum and fixed minimum), and the off-position. This is designated as two-stage burner operation.

Method (1), which involves the periodic operation of a burner operating at a fixed rate of input, was used in series A through D. The extent to which continuous heat delivery to the rooms was maintained depended to a great extent on the sensitivity of the room thermostat, the air-flow rate, and the operating range of the fan switch. Method (2), which involves the modulation of the input rate by means of a modulating type of room thermostat, appears to have desirable performance characteristics, but the investigation in the Residence did not include this method of approach. Method (3), which can also be designated as a high-low flame operation, utilizes a two-stage gas valve. The studies which were conducted with this method of operation have been designated as series E and F.

The purpose of these studies was to determine if by operating with a high fuel-input rate in cold weather and with a lower input rate in mild weather, the following desirable results could be obtained:

(1) A more continuous operation of the burner, together with a longer operating period of the blower, resulting in a more continuous delivery of heat to the rooms.

(2) Lower flue-gas temperatures, obtainable with the lower fuel-input rate in mild weather, which would reduce the flue loss during the off-period of the burner, and thus result in a fuel saving.

Series E was conducted with a single-speed blower with high speed operation and series F with a two-speed blower. Both of these series were conducted with the same equipment as was used in the previous

Table 6
Operating Conditions for Series E and F

Series	Air-Flow Rate, cfm	Fan-Switch Settings, F	Blower speed, rpm	Fuel-Input Rate, Btu per hr
E	High: 1225	Cut-in: 100 Cut-out: 80	Single-speed High: 538	Two-stage Low: 60 000 High: 90 000
F	Low: 800 High: 1225	Cut-in: 90 Low to High: 120 High to Low: 95 Cut-out: 80	Two-speed Low: 360 High: 538	Two-stage Low: 60 000 High: 90 000

series except for the room thermostat and gas valve. A two-stage thermostat with a heat-anticipating element in the high stage only, replaced the single-stage thermostat, and a two-stage gas valve replaced the single-stage gas valve. The operating conditions for the two series are shown in Table 6.

A fuel-input rate of 90,000 Btu per hr was selected for the high-stage input which was identical with the single input rate used in series A through D. A low-stage input of 45,000 Btu per hr was initially tried, but due to difficulty in obtaining proper ignition an input rate of 60,000 Btu per hr was finally selected. Since the low-stage input rate satisfied heating requirements up to eighty percent of the design temperature difference of 80 F, it was found that high-stage operation occurred only infrequently. For example, in series E the high-stage operation of the burner occurred only when the outdoor temperature decreased to 2 F so that this opeation occurred only for short periods and only during five days. Furthermore, in series F only one high-stage operation of ten minutes' duration occurred when the outdoor temperature decreased to 5 F. In addition, the blower did not operate at high speed except during this one high-stage burner operation, since the low input rate was not sufficient to provide a bonnet-air temperature greater than 120 F. For all practical purposes the types of operation obtained were equivalent to a high-speed blower used in conjunction with a low-stage burner (series E) and a low-speed blower in conjunction with a low-stage burner (series F).

(a) *Room-Air Temperature Differentials and Variations*

The room-air temperature differentials in the living zone were identical for the two series as shown in Table 7. However, a reduction in temperature at the ceiling level was obtained with series E.

For both series E and F some variation in room-air temperatures was apparent when the operation of the two-stage burner changed from low stage to high stage. The room thermostat required a decrease in room-air temperature of 1½ F below the thermostat setting before the high-stage burner circuit was closed. In actual operation, the burner operated continuously on low-stage for several hours preceding the change to high stage, during which time the room-air temperatures

Table 7
Room-Air Temperature Differentials for Series E and F

Indoor-Outdoor Temperature Difference, F		20	35	55	65
	Series	Temperature Differentials, F			
Floor Level to Breathing Level	E	1.5	2.5	3.9	4.6
	F	1.5	2.5	3.9	4.6
Breathing Level to Ceiling Level	E	1.0	1.4	1.9	2.2
	F	1.6	2.6	4.0	4.7
Floor Level to Ceiling Level	E	2.5	3.9	5.8	6.8
	F	3.1	5.1	7.9	9.3

gradually decreased 1½ F. Thus, during a lengthy period preceding the change to high-stage operation, the room-air temperatures were below the desired thermostat setting. The discomfort experienced during these periods could be alleviated by a manual adjustment of the room thermostat to a higher setting.

Although the duration of high-stage burner operation was only a small portion of the total operation, an unexpected type of operation was obtained which is worthy of note. It was observed that the variation in room-air temperature with respect to time was large for series F during high-stage operation. After a short period of high-stage burner operation the high-stage burner circuit opened, followed shortly afterwards by the opening of the low-stage burner circuit which shut off the burner. In the period that followed, the room-air temperature decreased rapidly to values below those normally experienced. Since this occurred only with the two-speed blower operation, it has been attributed to the sudden discharge of heated air into the rooms at the time of change from low-speed to high-speed operation. Low-speed blower operation was obtained as long as low-stage burner operation was maintained. However, when high-stage burner operation took place the bonnet-air temperature increased sharply until the time the blower started to operate at high speed. The delivery of heated air at high flow rates, together with the actuation of the heat-anticipating element in the room thermostat, resulted in a complete shut-off of the burner.

This infrequent occurrence was not observed in the case of series E. Since the blower operated only at high speed, the bonnet-air temperatures were relatively low as compared to series F. Furthermore, since there was no change in blower speed, and hence no sudden discharge of higher temperature air into the rooms, no overrun of the room-air temperatures occurred. Hence, when the high-stage burner circuit was opened, the low-stage circuit remained closed, and no disruption in heat supply was experienced.

(b) *Performance of the Blower*

The averages of the maximum and minimum bonnet-air temperatures for series E and F are shown at the top of Fig. 10. As might have been expected, the high-speed blower operation of series E resulted in lower bonnet-air temperatures. The longer total operating time of the blower with series F over the major portion of the heating season, was due primarily to the lower air-flow rate. In spite of this longer operating time, the electrical input for the low-speed blower operation with series F was less than that for the high-speed blower operation with series E. No difference was found in the average lengths of off-periods of the blower.

(c) *Performance of the Burner*

As may be seen from the performance curves for the burner at the top of Fig. 11, the average maximum flue-gas temperatures increased as the weather became colder. The greater heat transfer obtained with the high-speed blower operation for series E is reflected in the lower flue-gas temperature. While the CO_2 content of the flue gas was about 5.6 percent for each series, the lower flue-gas temperatures for series E resulted in a decrease in fuel consumption of approximately ten percent, as compared with that for series F.

Since the lower fuel consumption was obtained with series E it would be expected that the frequency of burner operations for series E would be less than those for series F. However, as may be seen in Fig. 11, this was not the case. A possible explanation may be attributed to the location of the room thermostat and to the difference in air-flow rates and hence the air velocities in the room. The room thermostat was located in the

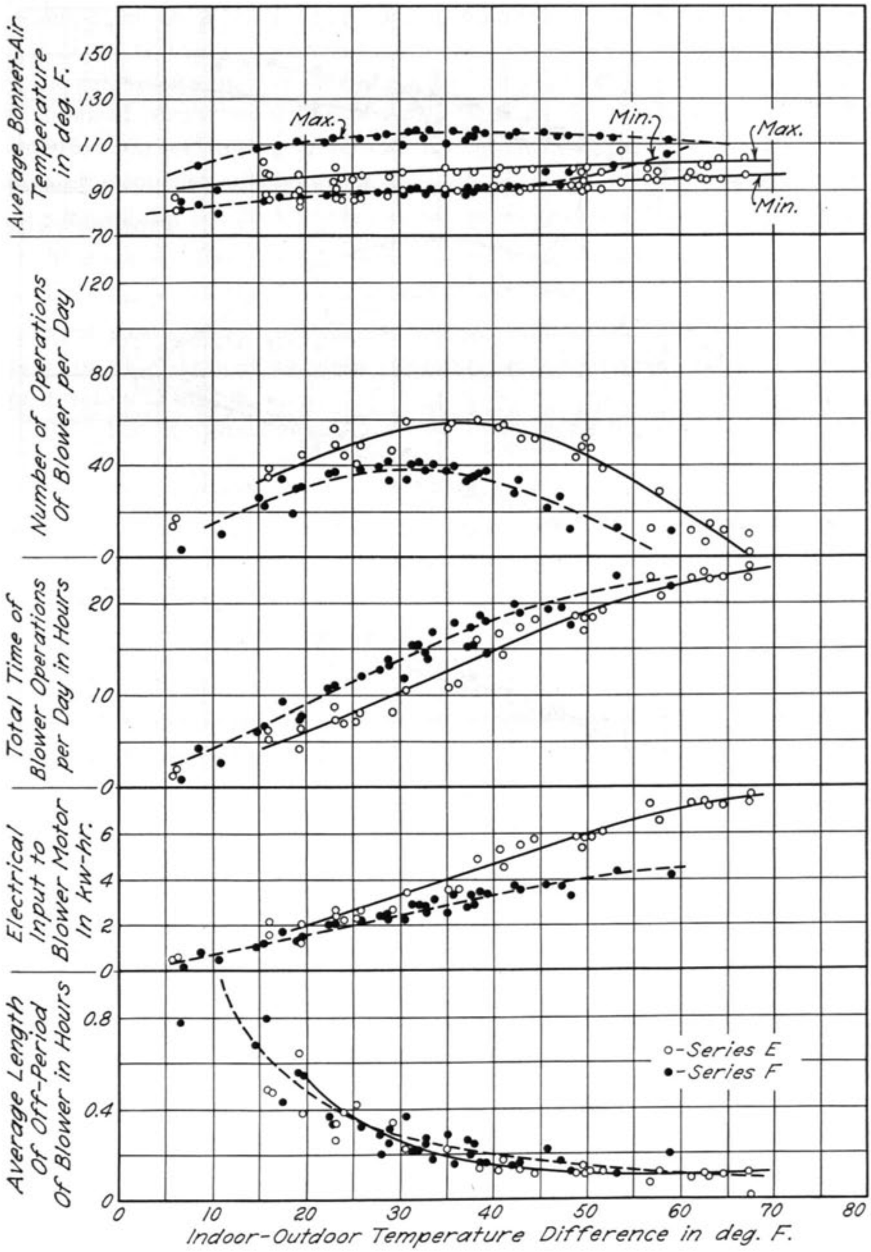

Fig. 10. Blower Performance Curves for Series E and F

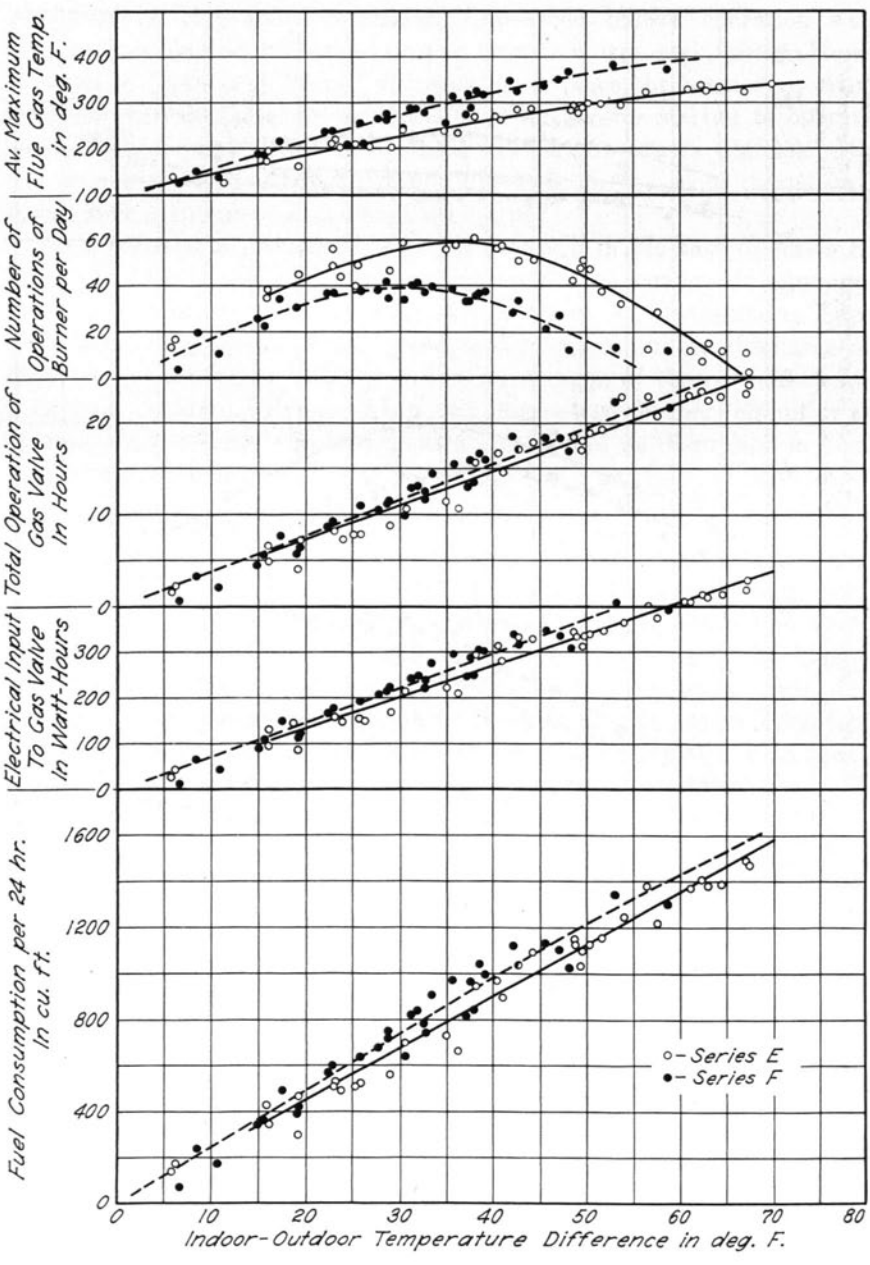

Fig. 11. Burner Performance Curves for Series E and F

dining room 60 in. above the floor, approximately 12 ft to the right and 3 ft ahead of the warm-air register. The low-speed operation for series F apparently did not provide as good circulation in the room as did the high-speed blower operation of series E. As a result, the thermostat was satisfied earlier during a burner operation in series E resulting in a greater frequency of operation.

(d) *Summary*

The results obtained with a two-stage burner operated in conjunction with a single- or two-speed blower may be summarized as follows:

(1) Although a two-stage burner and control was provided, the system for all practical purposes operated as a low-stage burner unit, for both series E and F.

(2) The performance obtained with the single-speed blower and low-stage burner operation was satisfactory.

(3) The particular thermostatic control arrangement used in these studies indicated the necessity for a modification in the arrangement to overcome the "drooping" characteristic of the thermostat in severe weather.

(4) Use of the low-stage burner and the two-speed blower (series F) resulted in an increase in fuel consumption of approximately ten percent over that obtained with the low-stage burner and the single-speed blower (series E). This was partly compensated for by a decrease in electrical input to the blower motor.

VI. SUMMARY AND CONCLUSIONS

14. General Observations

The results of the investigation indicate the importance of air-flow rate, fuel-input rate, and settings of thermostatic controls on the operation of the entire heating system. For these studies it should be emphasized that the duct system, the register sizes and locations, the furnace type, and the blower were unchanged. By making relatively minor changes in blower speed, fuel-input rate, or control settings, the variation in results reported in this bulletin was obtained. This indicates that for any heating system the optimum functioning of the system is dependent not only upon design but also upon the adjustments made after the system is installed.

Even though the heating system was subjected to an extremely wide range of operating conditions, it functioned for all practical purposes in an acceptable manner. The flexibility of a forced-air system was demonstrated by the fact that the thermostatic controls provided a relatively uniform air temperature at the thermostat location regardless of the changes in air-flow rate and fuel-input rate.

In the development of heating practice a number of empirical rules inevitably become formulated and over a period of time become accepted as necessary for satisfactory operation. Such an example was the rule that 6 air recirculations per hr were necessary for the design and operation of a forced warm-air system. It is probably true that under some conditions this rule-of-thumb may have been necessary. In the studies reported in this bulletin, however, no justification was found for this arbitrary rule, since air recirculations of 4.2 and 2.7 per hr resulted in satisfactory operation. Since the time of these studies even smaller air-flow rates, corresponding to an air-temperature rise of 100 F instead of 70 F have been accepted(7) as providing satisfactory operation during the entire heating season.

The results of all series from A through F are summarized in Table 8. Two sets of values are shown, one for an indoor-outdoor temperature difference of 35 F corresponding to an average winter day, and the other for 55 F corresponding to a colder day. A brief discussion of the results is presented in the following sections.

Table 8
Summary of Operating Conditions and Results

Series	A		B		C		D		E		F	
Operating Conditions												
Blower Operation	Single-Speed		Single-Speed		Two-Speed		Single-Speed		Single-Speed		Two-Speed	
Air-Flow Rate, cfm	1225		1225		Low: 800 High: 1225		800		1225		Low: 800 High: 1225	
Temperature Rise through Furnace, F	50		50		Low: 70 High: 50		70		35		Low: 50 High: 35	
Fan-Switch Settings, F	Cut-in: 100 Cut-out: 80		Cut-in: 155 Cut-out: 130		Cut-in: 90 Low to High: 120 High to Low: 95 Cut-out: 80		Cut-in: 90 Cut-out: 80		Cut-in: 100 Cut-out: 80		Cut-in: 90 Low to High: 120 High to Low: 95 Cut-out: 80	
Burner Operation	Single-Stage		Single-Stage		Single-Stage		Single-Stage		Two-Stage		Two-Stage	
*Values for Indoor-Outdoor Temperature Differences of 35 and 55 F**												
Room Temp. Differentials, F: Floor Level to Breathing Level	2.5	**2.1**	2.6	**3.0**	2.5	**2.3**	2.4	**3.0**	2.5	**1.9**	2.5	**4.0**
Room Temp. Differentials, F: Breathing Level to Ceiling Level	1.5	**3.9**	2.1	**4.0**	1.7	**3.7**	2.0	**3.7**	1.4	**3.9**	2.6	**3.9**
Room Temp. Differentials, F: Floor Level to Ceiling Level	4.0	**6.0**	4.7	**7.0**	4.2	**6.0**	4.4	**6.7**	3.9	**5.8**	5.1	**7.9**
Blower Operation, hr per day	10.9	**17.3**	3.9	**8.2**	16.6	**20.0**	17.7	**22.9**	12.3	**20.5**	15.6	**21.8**
Total Off-Periods of Blower, hr per day	13.1	**6.7**	20.1	**15.8**	7.4	**4.0**	6.3	**1.1**	11.7	**3.5**	8.4	**2.2**
Av Length of Off-Period of Blower, min	6.9	**4.0**	10.6	**9.4**	4.5	**2.8**	3.8	**1.0**	12.0	**6.6**	14.4	**18.8**
Major Blower Cycles per day	144	**101**	144	**101**	109	**107**	112	**110**	57	**32**	37	**7**
Electrical Input to Blower Motor, watt-hr per day	3750	**5800**	1700	**3300**	3500	**5100†**	3500	**4200**	3900	**6600**	2800	**4350**
Fuel Consumption, cu ft per day	760	**1230**	880	**1380**	810	**1280**	810	**1280**	790	**1245**	870	**1360**
Increase of Fuel Consumption over Series A, percent	....	....	16	**12**	9	**4**	9	**4**	4	**1**	14	**11**

* The values in bold-face type are for 55 F.
† Some amount of high-speed operation.

15. Comfort Evaluation

The problem of evaluating comfort in a field installation is complicated by the fact that the weather is never constant and the evaluation has to be made over a range of weather conditions. A complete listing of all factors, both large and small, which affect the comfort of the occupant would include the following items:

(1) Magnitude of air temperatures maintained by the thermostat.

(2) Uniformity of air temperatures in a horizontal plane in any particular room.

(3) Uniformity of air temperatures between rooms at a given time, and the degree to which this uniformity can be maintained over a range of weather conditions.

(4) Room-air temperature differentials between the floor level and breathing level.

(5) Variation of air temperatures in a room with respect to time.

(6) Relative humidities experienced over a fairly large range of weather conditions.

(7) Temperatures of surfaces enclosing the occupied space such as walls, ceilings, windows, and floors.

(8) Air movement within the occupied space.

(9) Noise due to equipment or air distribution devices.

Since the thermostat setting was 72 F for all studies reported in this bulletin and since variations from this desired temperature were slight, factor (1) may be disregarded in the evaluation of the comparative comfort. Likewise, factors (2), (6), (7), (8), and (9) may be disregarded also, since the changes made in the methods of operation for the different series would not have had an appreciable effect upon these factors. Hence, the evaluation of comfort has been limited to the temperature factors (3), (4), and (5).

The room-air temperature differentials in the living zone were essentially the same for all series, the differences in values being less than 0.3 F. The temperature differentials were small and considered to be acceptable in all cases.

In general, the balance of room-air temperatures was best maintained for those series in which the blower approached continuous operation and the bonnet-air temperatures were maintained at relatively low values. The most apparent unbalancing was observed with series B (high flow rate and high fan-switch settings) in which the gravity action during the off-periods of the blower resulted in slight overheating of the second- and third-story rooms and underheating of the sun room. This was particularly noticeable in mild weather operation.

16. Blower Operation

The total time of blower operation per day and the average length of off-periods may be used as indices of satisfactory operation of the system. From the standpoint of long blower operating times it may be seen from Table 8 that series C, D, and F were of equal merit. In all of these cases a low flow rate and low fan-switch settings were used. From the standpoint of short lengths of off-period of the blower, series C and D produced more favorable results than did series F.

At the time of the studies reported in this bulletin an empirical rule in common use was that 6 air recirculations per hr were necessary for satisfactory operation of a forced warm-air heating system. The results obtained in these studies, in which only 4.2 and 2.7 air recirculations per hr were obtained when the blower was operating, show no confirmation of the arbitrary value of six. As a matter of fact in order to obtain 6 air recirculations per hr, it would have been necessary to use a larger blower than that provided with the furnace-blower unit. Furthermore, air recirculations based only on the time of blower operation are misleading since the total time of operation of the blower per day should also be taken into account. The values in columns (4) and (5) in Table 9, for example, show that the average air recirculations per hour for the 24-hour period were much lower for series B than for series A, even though the same air-flow rate of 1225 cfm was used. In addition, the average recirculation for series B was also lower than those for series C, D, and F, in

Table 9
Recirculations of Room Air per Hour

Series	Air-Flow Rate, cfm	Air Recirculations per Hour		
		During Blower Operation Only	Average* for 24-hr Period	
			For 35 F In-Out Temp. Diff.	For 55 F In-Out Temp. Diff.
(1)	(2)	(3)	(4)	(5)
A	1225	4.2	1.9	3.0
B	1225	4.2	0.7	1.4
C	Low: 800 High: 1225	2.7 4.2	1.9 ...	2.3 ...
D	800	2.7	2.0	2.6
E	1225	4.2	2.2	3.6
F	Low: 800 High: 1225	2.7 4.2	1.8 ...	2.5 ...

* This assumes no air circulation during off-periods of blower and hence is on low side, particularly for series B in which "gravity" action occurred. Values in columns (4) and (5) were based on data given in Table 8.

which an air-flow rate of only 800 cfm was used. Therefore, from the standpoint of desirable blower operation, the number of air recirculations per hour during the time of blower operation is not a satisfactory index. Both the total time of blower operation and the average length of off-periods provide a better index for evaluating the relative effectiveness of blower operation in producing desirable temperature conditions.

Subsequent to the time of the studies reported in this bulletin, the warm-air heating industry has recognized the importance of long periods of blower operation. The trends indicated in these studies, namely that a 70 F temperature rise (800 cfm) was found to give more favorable operating conditions than did the 50 F temperature rise (1225 cfm), has led to the use of a temperature rise of 100 F. In the "continuous air circulation principle" advocated by the National Warm Air Heating and Air Conditioning Association,[7] the following operating conditions have been specified:

(a) The room thermostat temperature differential should be adjusted to its lowest practicable setting so as to cause short and frequent operations of the burner.

(b) The blower speed should be adjusted to produce a temperature rise through the furnace under continuous burner and blower operation of 100 F.

(c) The fan-switch settings should be as low as practicable to permit the blower to operate for long periods.

(d) The fuel-input rate should be adjusted to offset the heat loss of the structure under design conditions.

The trends indicated by the investigation reported in this bulletin show the validity of the "continuous air circulation" principle.

17. Operating Costs

The operation of the single-speed blower at a high flow rate and high fan-switch settings (series B) resulted in the lowest electrical inputs to the blower. However, this was due to the short operating periods of the blower and to the fact that the system was operating as a combination gravity and forced-air system.

Although the cost of electrical operation for series B was less than for the other systems, this advantage was more than offset by the increase in fuel consumption. The fuel consumption was lowest for series A and E for low temperature rises and low fan-switch settings. Slightly greater fuel consumptions were obtained with series C and D, possibly due to the lower bonnet efficiency accompanying the low air-flow rates as indicated by comparing tests 2 and 3 with 1 and 4 in Table 1.

During previous studies in the Research Residence with oil burners,[5] low fuel consumption was found to accompany low rates of fuel input. On this basis, it had been anticipated that the use of a two-stage gas burner would also result in a lower fuel consumption than was obtained with a single-stage burner. The actual results as shown in Table 8 indicate that such was not the case. As mentioned in Section 9, the flue-gas temperatures experienced with low-stage burner operation were markedly reduced over those experienced with high-stage operation. However, since it was not possible to reduce the openings for primary and secondary air to the burner, the CO_2 percentages of the flue gas also decreased sharply when the burner operated on the low-stage. The net result was that instead of obtaining a reduction in flue-gas loss with the decreased fuel-input rate, a slight increase was actually obtained. The most effective operation with two-stage or modulated type of burners would probably require adequate control of the air-fuel ratio at all fuel-input rates.

From the standpoint of total cost of operation, including both electrical and fuel costs, little difference existed between series A, C, and D, all of which were found to give favorable results from the standpoint of temperature control. As a matter of fact, even the greatest difference shown in Table 8 would probably be considered insignificant in practical field operation.

On taking into account the factors of temperature control, blower operation, and operating costs, the conclusion can be made that series C and D provided the best results. For both series low air-flow rates and low fan-switch settings were used. The additional complications of the two-speed blower arrangement in series C would probably make it less desirable than the simpler single-speed blower arrangement in series D.

In connection with the discussion of two-stage burners, it should be noted that series E and F were conducted with a specific arrangement of a two-stage burner and two-stage thermostat. These results cannot be extended to apply to all possible arrangements and types of two-stage burners and controls. Furthermore, during the short duration of these studies it was not possible to observe the effect of different operating temperatures on the life of the heat exchanger[4] in the furnace.

REFERENCES

1. Kratz, A. P., Konzo, S., and Thomson, D. W., "Combustion Efficiencies as Related to Performance of Domestic Heating Plants," University of Illinois Engineering Experiment Station *Circular 44,* 1942.
2. Willard, A. C., Kratz, A. P., and Day, V. S., "Investigation of Warm-Air Furnaces and Heating Systems, Part IV," University of Illinois Engineering Experiment Station *Bulletin 189,* 1929.
3. Kratz, A. P., and Konzo, S., "Investigation of Warm-Air Furnaces and Heating Systems, Part VI," University of Illinois Engineering Experiment Station *Bulletin 266,* 1934.
4. "The Effect of Modulated Operation on Performance of Gas Warm-Air Furnaces," *Research Bulletin 51,* American Gas Association Testing Laboratories, Cleveland, Ohio, 1948.
5. Kratz, A. P., and Konzo, S., "Investigation of Oil-Fired Forced-Air Furnace Systems in the Research Residence," University of Illinois Engineering Experiment Station *Bulletin 318,* 1939.
6. "Approval Requirements for Central Heating Gas Appliances," American Standards Association, Part VI, Gas Furnace Performance, Z 21.13 — 1945.
7. *Manual 6* — "Service Manual for Continuous Air Circulation Technicians," 1st edn., National Warm Air Heating and Air Conditioning Association, Cleveland, Ohio, 1947.

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